

Proposed Design Concept for Chassis and Wheels of an Autonomously Navigating Robot

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Summary

Autonomous, line following robots are being optimized and improved every day. These improvements in intelligence are maximizing human productivity, efficiency, and safety in work environments [1]. For this reason, a junior-level design course at Pennsylvania State University has tasked our team with designing an autonomously navigating robot. As stated in the project requirements [2], the robot should be able to follow a line using a differential drive mechanism and reflective infrared sensor. The robot should be able to start and stop autonomously at the beginning and end of a white line.

This document proposes design concepts for the chassis and wheels of an autonomously navigating robot that is to navigate a straight, outdoor course. To generate the design concepts for the chassis and wheels, our team made a functional decomposition chart. The functional decomposition chart is broken up into five subfunctions: support mass, move mass, store energy, decision making, and line following. Within these subsections are components including the chassis, wheels, motors, and components of an Arduino kit. Next, using the project requirements [2], our team decided upon seven prototype needs: portable, durable, fast, stable, autonomous, long battery life, and able to relocate the tack. After assigning metrics and specifications to each of those needs, our team generated three concepts for the chassis and three for the wheels. Using an Analytical Hierarchy Process (AHP) matrix, our team selected one concept for the chassis and wheel to prototype. The selected concept has a rectangular chassis with smooth wheels. In addition, the concept has four wheels, with the two front wheels being driven and the back wheels being non-driven.

Over the next seven weeks, our team is to produce and test a series of three prototypes leading to a final prototype. One challenge our team faces is trying to determine the correct wheel radius, so that the robot can maintain a low center of gravity, while also having large enough wheels to maximize speed. The final prototype, known as the Beta Test, is to be completed on April 25, 2023.

Statement of Problem

The use of autonomously navigating robots is becoming more prevalent, especially within warehouses of the growing industry of online shopping. Line-following robots can be used to streamline in-house transportation and improve overall efficiency of a warehouse [3]. Unlike traditional human operated machinery, these robots are autonomously configured to follow tracks inside a factory or commercial space.

To further investigate and understand these robots, the Design Methodology course (ME 340) at Pennsylvania State University has tasked our team with designing an autonomously navigating robot that is to navigate the course shown in Figure 1. The course is a straight line with the intensity of whiteness decreasing at the end of the line. According to project requirements [2], the robot needs to be able to autonomously travel along a straight line outdoors and stop at the end of the track, with each robot having one unique feature. Our teams' primary requirements for the chassis are to support the weight of the robot and be durable. Regarding the wheels, the main requirements we decided on were speed, durability, and reaction time.

The main parts of our robot are the infrared sensor, Arduino circuit and motors. IR sensors function by emitting a 940-nanometer light wave that will reflect from the surface back towards the sensor. The white line course is detected using the IR sensor which then relays the data to the Arduino circuit. Then, a decision is made to either move straight or turn to a side by triggering the motors respectively.



Figure 1. Course that our robot is to navigate [2]. The key aspect to this course is speed. However, one aspect that is challenging is that the line gets dimmer the further the robot travel and the robot has to autonomously stop at the end of the line.

At this stage of the project, our team has generated three different designs for both the wheels of the robot and the chassis, both of which will be 3D printed. Moving ahead, we will conclude the best design and continue testing and prototyping on the final design choices. Our team has also successfully tested the IR sensor alongside the code for running the motors. We were able to configure the circuit to slow down the motors when the IR sensor detected less light, similar to when the white line fades away. Similarly, the motors speed up or continue running at full speed when reflecting more light. >

Proposed Design Concepts

This document proposes design concepts for the chassis and wheels of an autonomously navigating robot that is to navigate the outside course. One assumption for our robot is that the code and the basket that carries materials will be developed during the prototyping stage for improvement. Although some code has been tested, the main development of the code will be after the wheels and chassis are 3D printed to test the delays and speed of the body of the robot. These delays within the code will determine the reaction time of the robot to ensure that it will start and stop at the beginning and end of the line. The basket will need to be the walls of the chassis so that materials will not slide out upon the robot's acceleration. This feature cannot be tested until the chassis is printed.

The infrared sensor creates limitations on the design of our robot. One limitation that the robot will face is noise in the infrared sensor data [3]. This noise is caused by reflections from the sunlight that the IR sensor will receive that can direct the robot away from the line. In addition, because the white line becomes dimmer as the course progresses, the sensor will have to react to the line accordingly. Similarly, the reaction time on the robot is limited because it is controlled only by what it can see at the time and it cannot anticipate what is coming outside of the detection zone of the IR sensor, unlike a human controlling a vehicle.

The next five subsections present the process that our team followed for selecting design concepts to prototype. Presented in the next subsection is the function structure and system decomposition. The next subsection presents the needs and metrics of the prototype. In the third and fourth subsections, the concept generation and concept selection processes are shown. Lastly, in the fifth subsection, a CAD drawing is shown for the concept that is chosen for the chassis and wheels.

Function Structure and System Decomposition

To identify the sub-functions and parts of the robot, our team developed a diagram for the functional decomposition for our autonomously navigating robot. In Figure 2, the function structure and system decomposition diagram display the sub-functions, parts, inputs, and outputs of our robot. It is important to understand how the software and hardware function together so that the robot can autonomously navigate the course. The performance of the robot is dependent on the success of the sub-function interactions.

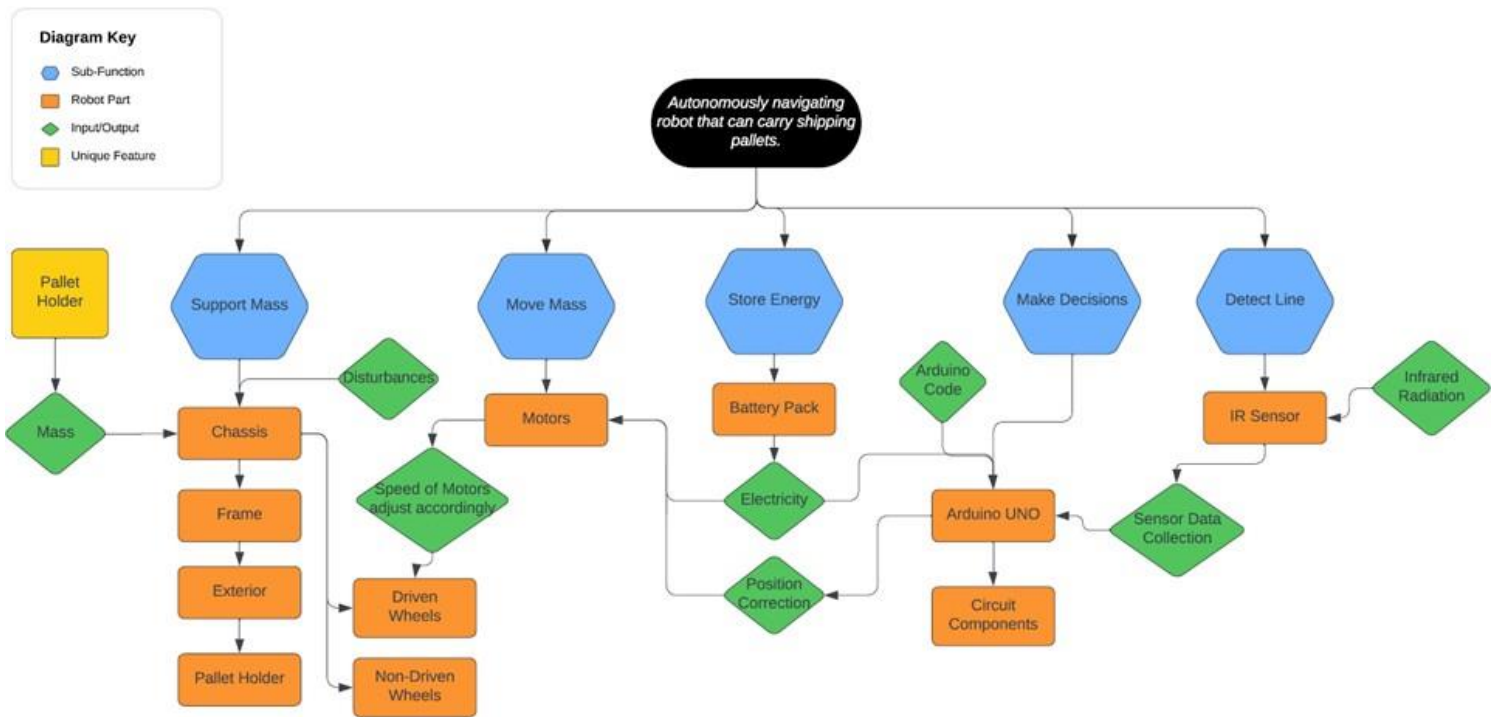


Figure 2. System decomposition of our autonomously navigating robot. The black bubble indicates the overall function of the robot. The diagram key shows what each shape represents. Blue hexagons represent the sub-functions. Orange rectangles represent the parts of the robot. Yellow square represents a unique feature. Lastly, the green diamonds represent the inputs and outputs.

For the robot to operate, there are a few important inputs needed. The interaction of the inputs and outputs with parts creates the sub-functions of the robot. First, our robot needs to be able to support mass and withstand disturbances. Therefore, the chassis, wheels, and frame will be designed to support and satisfy these sub-functions. The unique feature corresponds with the sub-function of supporting the mass. As shipping pallets are a staple in the manufacturing industry, our group decided to attach a pallet holder on top of the robot. Such pallets can serve additional roles such as protecting the product, absorbing the stresses, and holding the weight. Additionally, the robot needs to be able to store electricity. Electricity from the battery pack is necessary to power the Arduino Uno, motors, and infrared sensor. To meet customer needs, the robot needs to travel quickly on the straight-line course. Two motors will be used to move the mass of the robot. Many of the inputs, outputs and parts are interconnected with each other and not subjected to one sub-function.

Outside of the manufactured parts, the autonomously navigating robot will require code to interpret data collected from circuit components. To detect the white line, infrared radiation data is collected from the infrared sensor and sent to the Arduino Uno. The objective of the code is to interpret the data collected from the infrared sensor and adjust the speed of the motors accordingly. A continuous loop will be necessary to ensure the robot continues the path for the duration of the track. Additionally, there will be a final stopping condition to stop the robot.

Prototype Needs and Accompanying Metrics and Specifications

This subsection presents the prototype needs and accompanying metrics and specifications for the design of our autonomously navigating robot. The first step was to identify our customer and analyze what exactly the target audience would want the robot to do. Because our customer is online shopping warehouses, we came up with the following customer needs: portable, durable, stable, autonomous, fast, relocates track, and has a high battery life. For instance, the customer needs the robot to be fast as warehouses want to maximize efficiency and decrease transportation time.

Based on these needs, we have restrictions on various metrics which then correspond to exact specifications. Metrics are aspects of the robot that can be measured, and the specifications are the exact numerical values for said metrics. These prototype needs, metrics and target specifications as shown in the Quality Functional Deployment (QFD) chart in Table 1. One such specification is the robot should be between 3 kg and 6 kg and under 0.025 cubic meters in volume so that the robot can be moved easily. The total weight of the robot includes the batteries that power the robot, which are standard AA batteries that will operate at a maximum of 6 volts.

Table 1. QFD Chart demonstrating the needs, metrics, and specifications of our design.

		Metrics									
		Total Weight	Total Volume	Speed	Acceleration	Reaction Time	Force to Tip Over	Compressive Force to Break	Tensile Force to Break	Center of Gravity	Battery Voltage
Customer Needs	Portable	X	X								
	Durable	X						X	X		
	Stable	X			X		X			X	
	Autonomous					X					X
	Fast	X		X	X	X					
	Relocates Track			X	X	X					X
	High Battery Life	X		X							X
Min:		3 kg	N/A	.8 m/s	.6 m/s^2	N/A	40 N	100 N	80 N	N/A	1.5 V
Max:		6 kg	0.025 m^3	N/A	N/A	0.1 s	N/A	N/A	N/A	.1 m	6 V
		Target Values									

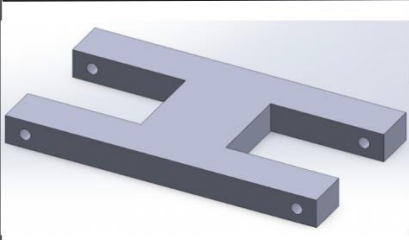
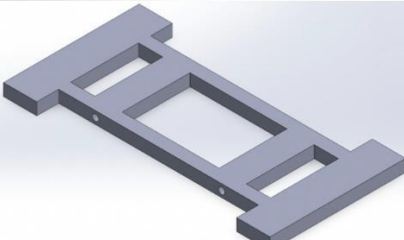
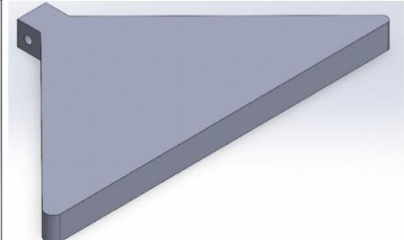
An important part of the robot's stability is the center of gravity, which cannot exceed 0.1 meters above the ground. Keeping the center of gravity low to the ground will increase the force needed to tip over the robot, which should be no lower than 40 Newtons. Similarly, the compressive force that the robot should be able to withstand is 100 Newtons to avoid bending and breaking. Also, while the robot will not likely ever be under tension, it should be able to take 80 Newtons of tensile force.

Lastly, the robot should be able to travel quickly enough in order to complete the course in less than 3 seconds. Three areas that determine if the course can be completed that quickly are speed, acceleration, and reaction time. The speed will be greater than 0.8 m/s and the reaction time should be less than 0.1 seconds. Finally, acceleration of the robot should be at least 0.6 m/s² so that the robot can reach maximum speed in half a second.

Concept Generation

Our team's concept generation process began with analyzing the problem, customer needs and functional decomposition. Each of these steps assisted us in brainstorming initial ideas for the wheel and chassis. The next step was to narrow down to the three most realistic and effective designs for the wheels and chassis. Every design concept had aspects that needed to be developed, keeping in mind constraints whole not limiting quality or creativity. These final three designs are tabulated and illustrated in Table 2 for the chassis.

Table 2. Design concepts for chassis of our autonomously navigating robot.

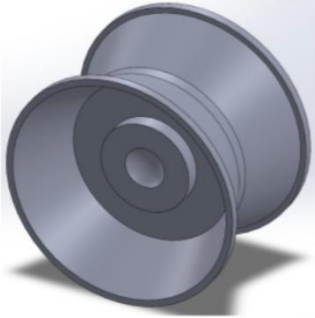
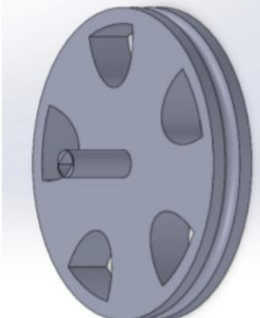
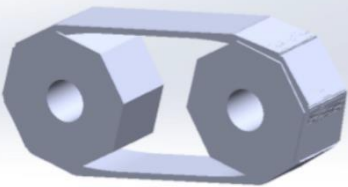
Design Concept 1: H-shaped chassis	Design Concept 2: Rectangular Chassis	Design Concept 3: Triangular Chassis
		

Our first concept for the chassis, design concept one in Table 2, is an H- shaped chassis with holes for mini axles. For this design, the wheels will be directly connected to the motors using mini axles going through the designed holes on the far end of the chassis. The Arduino circuit will be firmly attached to the middle section with more area ensuring the robot is balanced. Because the front wheels will guide the robot, the two motors and IR sensors will be attached toward the front of the chassis on the front axle. For this reason, we may need to add some deadweight to the rear end of the chassis to ensure stability and balance.

Design concept two is a rectangular shaped chassis with two beams connecting the front and back of the chassis. In this area, there are three rectangular holes cut which result in two more beams forming. These beams are where the two mini axles will be attached, connecting to the wheels. The front beam will secure the IR sensors and motors which can rest on the beam, leaving the remaining circuit to be attached to the rear beam. After prototyping, we can balance out the 2 beams based on which beam has more load, resulting in a stable and balanced robot.

Design concept three is a triangular shaped chassis with a single hole at the top for an axle. With the steering wheels at the front connected by a single axle, the rear end will only require two caster wheels on each side to provide control and balance. The motors and IR sensor will need to be attached to the front, leaving the rest of the circuit adhered to the middle and sides appropriately, ensuring stability. All the chassis concepts will need to interact with the three different wheel concepts seen in Table 3.

Table 3. Design concepts for wheels of our autonomously navigating robot

Design Concept 1: Off-Road Wheel	Design Concept 2: Smooth Wheel	Design Concept 3: Treads
		

Illustrated by design concept one in Table 3 is our first design concept for the wheels. This wheel is an off-road wheel with a hole in the center for the mini axle. Features of the wheel include durable spokes and a rough, off-road exterior tire (not shown). This tire results in good grip and overall, a durable and long-lasting wheel. Design concept two is a smooth wheel with a hole in the center for the mini axle. This wheel is more aerodynamic due to the spokes and simple exterior of the tire. This design concept results in a more balanced and effective wheel with greater potential for high speeds and minimum weight. Our team's third design concept is a tank-like tread with the track connecting to two gears/road wheels. The front road wheel will act as the driving gear, whereas the rear wheel will be non-driving. The track is a geared band of treads that provide maximum durability and can support a much higher mass than what is necessary for this robot.

Concept Selection

After generating concepts for chassis and wheel design, these concepts were put into a concept scoring matrix our team created. As shown in Table 4 and Table 5, the concept scoring matrix is used to rank the concepts to determine the best concept for each subfunction. To create the concept selection matrix, an AHP matrix was used to accurately weigh the needs. Details about the process with the AHP matrix can be found in Appendix A. From the AHP matrix, our team was able to determine the weights for the needs: cost, size, durability, reaction time, speed, and unique feature.

When determining which chassis concept will perform the best for the team's robot function, there are two main standards. First is how well the concept ranked in the scoring matrix with the five customer needs. The rectangular chassis ranked the highest out of the three concepts as it was the most durable and fast. The second standard is how feasible the team thinks it is to make that chassis. Since rectangular shaped chassis are common for automobiles and the concept has simple geometry, the chassis will be easily manufactured. Because the rectangular chassis meets the two main standards, our team will use this chassis in our design.

Table 4. Concept scoring matrix for chassis design concepts.

	Weight	Triangular Chassis		H-Shape Chassis		Rectangular Chassis	
		Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Cost	6.20%	7	0.4340	4	0.2480	6	0.3720
Size	9.60%	8	0.7680	6	0.5760	5	0.4800
Durability	22.20%	2	0.4440	6	1.3320	8	1.7760
Reaction Time	19.70%	2	0.3940	7	1.3790	7	1.3790
Speed	37.80%	2	0.7560	6	2.2680	7	2.6460
Unique Feature	3.40%	2	0.0680	5	0.1700	7	0.2380
Total Score		2.8640		5.9730		6.8910	
Rank		3		2		1	

Selecting which wheel concept will perform the best for the team's robot design had the same process as the chassis concepts. The smooth wheel ranked the highest in cost, size, and speed criteria. Our team also considered how the wheel will interact with the selected chassis concept. A rectangular shape of the chassis will enable the wheels to easily connect to the motor. Lastly, the geometry of the wheel can be 3D printed with ease. All these factors were considered when selecting the smooth wheel.

Table 5. Concept scoring matrix for wheel designs

	Weight	Off-Road		Smooth		Treads	
		Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Cost	6.20%	5	0.3100	7	0.4340	2	0.1240
Size	9.60%	5	0.4800	7	0.6720	2	0.1920
Durability	22.20%	6	1.3320	4	0.8880	8	1.7760
Reaction Time	19.70%	7	1.3790	6	1.1820	1	0.1970
Speed	37.80%	6	2.2680	8	3.0240	3	1.1340
Unique Feature	3.40%	5	0.1700	5	0.1700	6	0.2040
Total Score		5.9390		6.3700		3.6270	
Rank		2		1		3	

CAD Drawing of Selected Design Concept for Chassis and Wheels

Once the final design concepts were decided upon, we created a computer-aided design (CAD) model on SolidWorks. CAD models show a detailed representation of how the robot would look. Also, CAD modeling creates files that can be used for 3D printing. Shown in Figure 3 is the model of the selected wheel design concept. Key parts of the design are the spokes, groove, and connection for the motor.

The groove is needed to hold the O-ring to give the wheel grip. Additionally, the connection of the motor has important tolerances to have a tight fit with the motor. Shown in Figure 4 is the model of the selected chassis design concept. Our design includes bumpers to protect the wheels and motor from disturbances. The two axles will contain the drivetrain system and provide a platform for the frame to be built upon. Detailed drawings for the wheel and chassis are included in Appendix B.

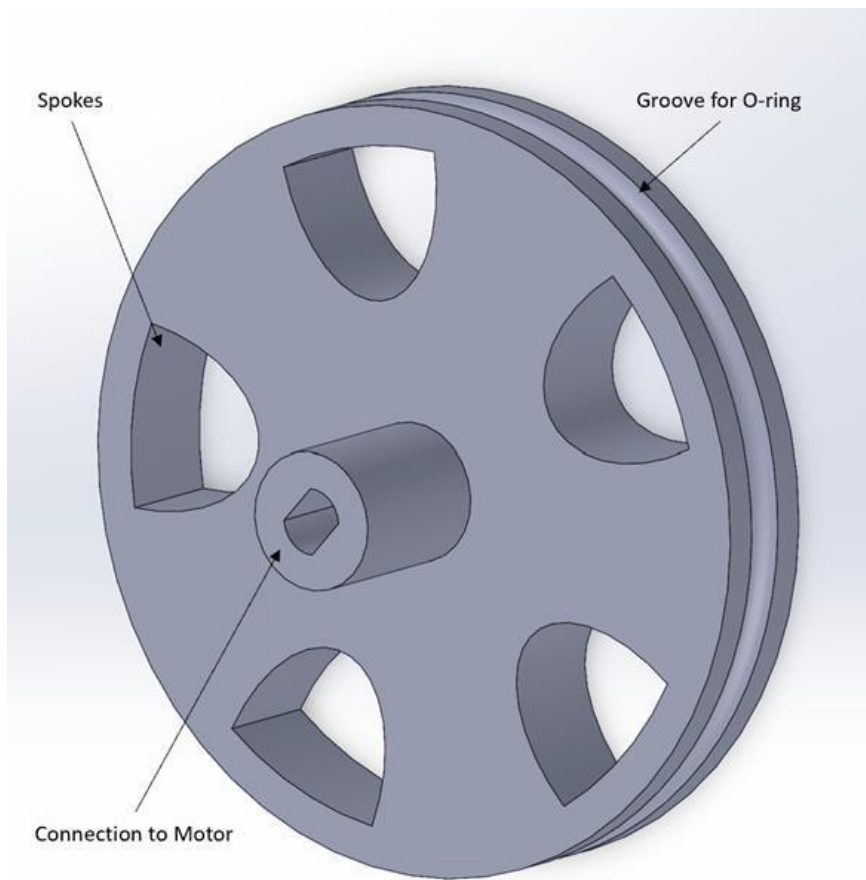


Figure 3. Isometric view of wheel CAD drawing.

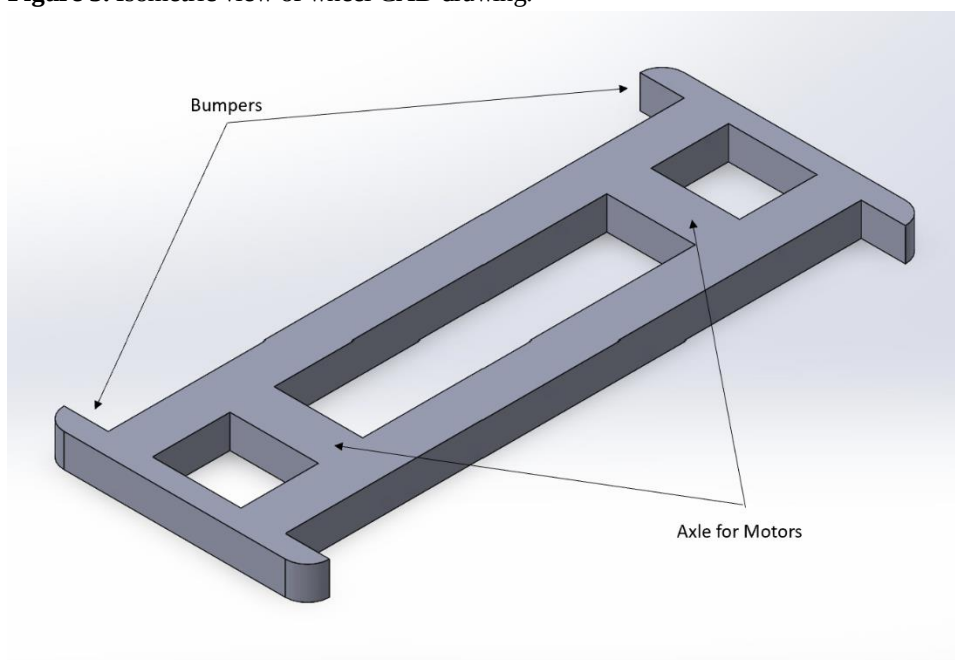
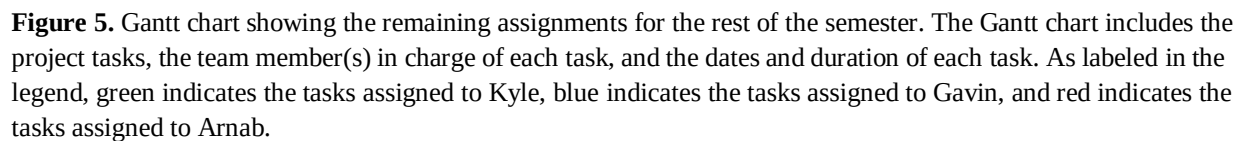


Figure 4. Isometric view of chassis CAD drawing.

This section presents the management plan our team intends to use and follow closely to complete the remainder of the assignments. Our team decided to use a Gantt chart to tabulate these assignments, which can be seen in Figure 5. The Gantt chart includes the assignment title, which member(s) of the group are to carry out the assignment, the start and due date of the task, and the duration of the task. Also, the chart provides a visual representation of the task compared to the amount of time required to complete the task. To summarize, three major upcoming assignments are the alpha 1 & 2 prototypes and the final beta prototype. Alongside the major assignments, we have included some smaller tasks as well, including testing the code and the assembly of the various parts of the robot. Because our Gantt chart includes the upcoming assignments for the remainder of the semester, we started the dates beginning at week seven.



One important aspect to note is that our team is qualified to complete this project. Not only did we complete thorough and extensive research on the robot but have followed that up by completing various important tasks in the process of manufacturing the robot. The Gantt chart is a good example to show that we are organized in our thoughts and plans. Additionally, our team has a variety of physical and technical skills which supplement our work in this project. Combined with a short biography and background, Appendix C presents our member's qualifications and technical skills.

Appendix B: Detailed Part Drawings

This section presents the detailed drawings of the wheel and chassis that will be fabricated for the alpha one prototype. In Figure B-1, the dimensions and features of the final selected wheel design are shown. To integrate with other parts, the dimensions of the groove and motor connection need to fit within the tolerances. Also, the geometry of the spokes can be visualized. Including spokes in the wheel design allows the wheel to be lighter without removing any needed surface area. Shown in Figure B-2 is the drawing of the selected chassis design concept. Overall dimensions are highlighted and fulfill the requirement of being under one cubic foot. Also, the main support beams are wider than the rest to be capable of supporting the mass. The wheel and chassis dimensions may be subject to change with further prototype testing.

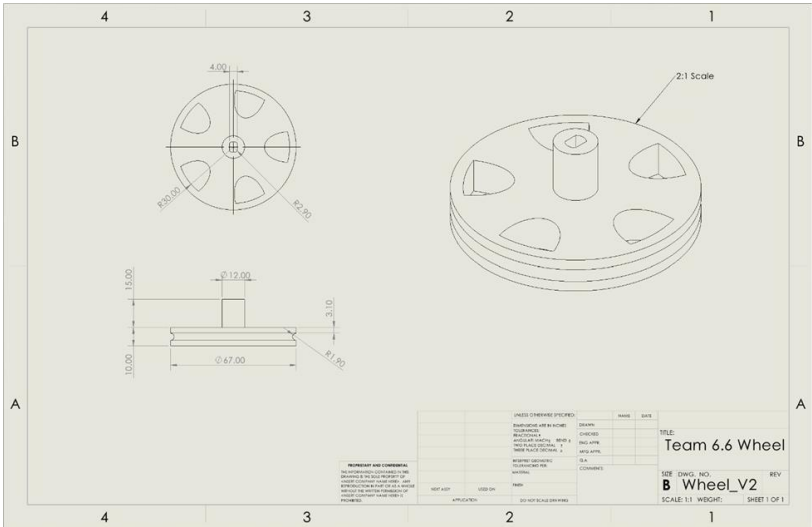


Figure B-1. Dimensioned part drawing of wheel.

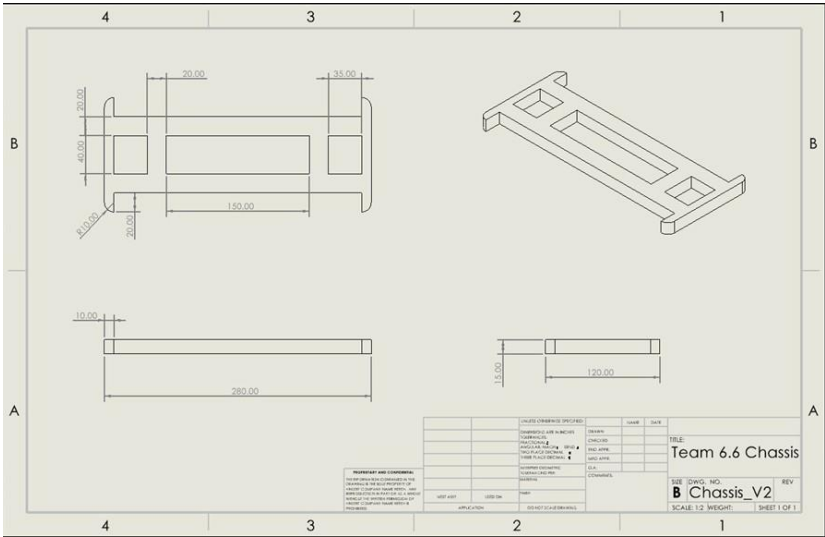


Figure B-2. Dimensioned part drawing of chassis.

Appendix C: Qualifications of Design Team

The following appendix introduces the members from the design team of the line- following robot. Each member has a brief description based on who they are, where they are from and their qualifications to work on this project. Shown in Figure C-1 is Kyle Good, Figure C-2 is Arnab Gupta and Figure C-3 is Gavin Knox.

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Figure C-1. Photo of Kyle Good

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Kyle Good is a junior studying mechanical engineering at Pennsylvania State University. He is from Newtown, Connecticut where he graduated from Newtown High School in June of 2020. At Penn State, Kyle is a member of the American Society of Mechanical Engineers as well as being a part of Alpha Phi Delta fraternity, where he served as a member on the judicial board. Kyle's skills include CAD (Computer Aided Design), Microsoft Excel, data analysis, and leadership. In his free time, he enjoys watching sports and being outside with his friends.



Figure C-2. Photo of Arnab Gupta

Arnab Gupta is a junior majoring in mechanical engineering at Pennsylvania State University. Originally, born in India, he grew up in 3 different countries including Kenya and U.A.E. He had an internship at 3M India in the personal safety division with a focus on welding during his senior year summer in high school. Arnab is a proud member of the American Society of Mechanical Engineers (ASME), an invited member of the National Society of Leadership and Success (NSLS) and the PSU Chess Club. His other hobbies include but are not limited to, playing, and watching soccer and tinkering with 3D printing. His main skillset includes excellent teamwork skills, organization and time management, and adaptability.



Figure C-3. Photo of Gavin Knox

Gavin Knox is a junior at Pennsylvania State University majoring in mechanical engineering with a minor in engineering mechanics. He was born and raised in Annville, Pennsylvania, where he graduated from Annville Cleona Highschool in May of 2020. At Penn State, Gavin is a member of the American Society of Mechanical Engineers (ASME) and Engineering Leadership Society (ELS). He is also the current President of Alpha Phi Delta Fraternity. The past two years, Gavin has been working at Reading Bakery Systems as an engineering intern developing his mechanical designer skills. These skills consist of CAD, drafting, project management, and leadership. Other hobbies and interests he has include 3D printing, scuba diving, and hunting.

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